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Optimised collision avoidance for an ultra-close rendezvous with a failed satellite based on the Gauss pseudospectral method

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ABSTRACT

This paper presents a trajectory planning algorithm to optimise the collision avoidance of a chasing spacecraft operating in an ultra-close proximity to a failed satellite. The complex configuration and the tumbling motion of the failed satellite are considered. The two-spacecraft rendezvous dynamics are formulated based on the target body frame, and the collision avoidance constraints are detailed, particularly concerning the uncertainties. An optimisation solution of the approaching problem is generated using the Gauss pseudospectral method. A closed-loop control is used to track the optimised trajectory. Numerical results are provided to demonstrate the effectiveness of the proposed algorithms.

1. Introduction

A failed satellite in orbit occupies an orbital resource and increases the probability of collisions, which poses a serious potential threat to space activities. Two types of effective measures are generally taken to reduce the amount of unavailable satellites: on-orbit repairing techniques that use a space robot and de-orbiting strategies that use a space tug. Related studies and demonstrations have been recently developed, such as the Orbital Express (OE) demonstration mission [1,2], the Micro-satellite Technology Experiment (MiTEx) programme [3], and the Spacecraft for the Universal Modification of Orbits (SUMO) project [4–6]. The OE mission, which was developed by Defence Advanced Research Projects Agency (DARPA), preliminarily demonstrated the feasibility of autonomous on-orbit servicing of spacecraft in the LEO orbit. The MiTEx project, which was a joint project of DARPA, USAF and USN, demonstrated the ability to conduct space surveillance and reconnaissance on non-cooperative targets in the GEO orbit. The SUMO project, which was renamed the Front-end Robotics Enabling Near-term Demonstration (FREND) project [7], followed up the preceding missions of DARPA and exhibited the development of on-orbit capturing and de-orbiting technologies using satellites in the GEO orbit [8].

One of the technical elements, "close-distance proximity", is significant for the development of a mitigation strategy before the capturing. This operation in space has drawn more attention due to less cooperation with the ground, particularly during ultra-close proximity to the target where collisions can occur. Numerical optimisation techniques have been used to solve the problems of spacecraft motion planning and trajectory optimisation for proximity. A heuristic plan was presented for a simple planar case in reference [9]. This proposed planning method consisted of parameterising the possible trajectories via a spline representation and numerically optimising the trajectories against a cost function. In reference [10], the collision avoidance, trajectory optimisation, and fleet assignment problems were combined into a single mixed-integer linear programme (MILP). The necessary logical constraints for avoidance were appended to a fuel-optimising linear programme by including binary variables in the optimisation. This programme was then followed by a feasibility MILP (FMILP) [11]. The algorithm improved the sequential linear programming (SLP) by identifying feasible solutions that were more optimal than a given value of the cost function. Reference [12] analytically formulated the problem of minimum-time and minimum-energy

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optimal trajectories of a rendezvous using the Pontryagin minimum principle. A collision avoidance condition was also imposed. The optimal control problems were numerically solved using a direct collocation method based on the Gauss pseudospectral approach. These examples show several different methods to combine optimisation and constraint satisfaction problems with flexibility and efficiency. Building on these efforts, this paper addresses a mission for a chasing spacecraft operating in an ultra-close proximity to a failed satellite that involves open-loop trajectory planning, closed-loop control and posture alignment.

When the failed satellite is an uncontrolled target with a complex configuration and high-speed rotation, approaching it without collision is challenging for the rendezvous mission. In this paper, we will focus on the trajectory planning of the manoeuvre problem. Importantly, the configuration and relative motion of the target are incorporated. A fuel-optimal path under constraints that account for collision avoidance and boundary conditions is proposed. The optimal solution is obtained using the Gauss Pseudospectral method (GPM) [13]. Notably, a closed-loop control method is used to track the optimised trajectory with feedback linearization to propagate a truly optimal and dynamic trajectory. In addition, the orientation of the chaser varies to constantly monitor the target. The desired attitude trajectory is generated based on the relative positions of the chaser and the target.

The contributions of the present paper are two-fold. Most dynamics and control schemes for proximity are presented using the Clohessy-Wiltshire (or Hill's) equations, as in references [14,15]. However, to directly measure the safe distance between two spacecraft and track the docking point, which is fixed on the tumbling target, the attitude information of the target must be introduced to the orbital dynamics. Thus, a novel model of relative motion has been established in the rotary coordinate, i.e., the target body frame. Moreover, since the mission scenario is constructed using an ultra-close proximity, the no-fly zone should be at least the minimum external geometrical form around the target. Unlike the traditional ellipsoid (ellipse) envelope model of a target with solar panels [16,17], a "sphere+ellipsoid" composite envelope model is introduced to save space. In particular, the concept of the error ellipsoid, which relies on the covariance information from the relative navigation system, is used in the trajectory planning as a substitute for measuring uncertainties. This substitution better approximates the actual situation and has greater practicality and applicability. Finally, the issues of closed-loop control and posture alignment are investigated for mission completeness.

The remainder of this paper is organised as follows. Section 2 introduces the problem formulation of the two-spacecraft rendezvous. Section 3 synthesizes the collision avoidance constraints of ultra-close proximity. Section 4 presents a methodology to solve the optimal control problem. Numerical simulations are shown in section 5 to obtain and verify the optimal solutions, and the conclusions are provided in section 6.

2. Two-spacecraft rendezvous modelling and formulation

Fig. 1 depicts the two-spacecraft rendezvous system, which has a target spacecraft that passively tumbles and a chaser spacecraft that actively approaches the target. A "sphere+ellipsoid" composite envelope model is used to graphically represent the target because its length in one direction is much longer than the other directions due to the solar panels. The chaser is represented by the blue sphere in Fig. 1. The geometrical forms are precisely circumscribed around the structure of the spacecraft.

We start from an arbitrary relative position (Fig. 1a) and bring the two spacecraft together for docking (Fig. 1b). The position of the docking point, which is fixed on the target, varies with the attitude variation. To directly describe the relative position between the chaser and the docking point on the target, the orbital dynamics of the relative motion are established in the body coordinate frame, which is centred at the centre of mass (CM) of the tumbling target spacecraft, where the x axis is located on the centre line of the solar panels, the y axis points towards the orientation of the exhaust nozzle, and the z axis is along the direction of the antenna. The position vector of the CM of the chaser with respect to the CM of the target in this frame is expressed as $\rho \in \boldsymbol{R}^n$. The dynamics equation of the two-spacecraft system is derived as

$$\ddot{\rho} = -\dot{\omega}_{tb}\times\rho - 2\omega_{tb}\times\dot{\rho} - \omega_{tb}\times(\omega_{tb}\times\rho) - \frac{\mu}{r_t^3}\left[\rho - 3\frac{\boldsymbol{r}_{tb}^T\rho\boldsymbol{r}_{tb}}{r_t^2}\right] + \boldsymbol{f} \tag{1}$$

where $\boldsymbol{f} \in \boldsymbol{R}^n$ is the applied control on the chaser, which is expressed in the target body frame; $\omega_{tb} \in \boldsymbol{R}^n$ is the target angular velocity with respect to the inertial frame, which is expressed in the target principal body coordinate frame; $\dot{\omega}_{tb} \in \boldsymbol{R}^n$ is the target angular acceleration; $r_t \in \boldsymbol{R}$ is the orbital radius; and $\boldsymbol{r}_{tb} \in \boldsymbol{R}^n$ is the absolute position vector of the CM of the target, which is expressed in the target body frame and obtained via

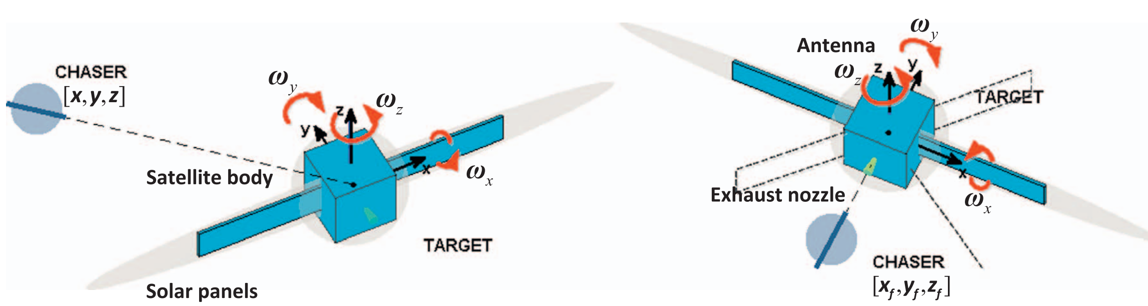
$$\boldsymbol{r}_{tb} = \mathbf{C}_{tb}^{o}\begin{bmatrix}0 & 0 & r_t\end{bmatrix}^{\mathrm{T}} \tag{2}$$

Note that the rotation matrix $\mathbf{C}_{tb}^{o} \in \boldsymbol{R}^{n\times n}$ is constructed to represent the coordinate transformation between the target body frame and the orbit frame. The centre of the orbit frame is fixed to the CM of the target. The x_o axis is along the velocity vector of the target. The y_o axis is located on the orbit normal of the target and the z_o points towards the centre of the Earth on its orbital radius.

To develop the optimal control, the dynamics Eq. (1) is rewritten in a state-space form as

$$\dot{\boldsymbol{X}} = \boldsymbol{A}(\boldsymbol{X}) + \boldsymbol{B}\boldsymbol{U} \tag{3}$$

where $\boldsymbol{X} \in \boldsymbol{R}^{2n}$ is the state vector; $\boldsymbol{A}(\boldsymbol{X}) \in \boldsymbol{R}^{2n\times 2n}$ is the state function; $\boldsymbol{B} \in \boldsymbol{R}^{2n\times n}$ is the control matrix; and $\boldsymbol{U} \in \boldsymbol{R}^n$ is the translational force (control). They are defined as



a. Arbitrary initial state **b. Desired final state**

Fig. 1. Depiction of the two-spacecraft rendezvous problem. a. Arbitrary initial state b. Desired final state.